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A two-stage MCDM model for reverse logistics network design of waste batteries in Turkey

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ABSTRACT

Inadequate environmental resources and overpopulation reveal the need to protect and recover natural resources attentively. In this sense, the reverse logistics concept emerged as a key solution since it deals with product flow from the final user to the origin. There are various items that need to be considered in well-planned reverse logistics network designs and one of these items is batteries which include hazardous and precious materials in it. Hence, waste management of batteries via recycling becomes a very significant issue from both economic and environmental benefits. Accordingly, depending on the importance of the topic, a two-stage methodology is proposed in this study for providing a network design under multiple objectives. Within the first stage, the importance weights of objectives are obtained via Spherical Fuzzy Analytical Hierarchy Process (SF-AHP) and they are found as 0.248 for cost minimization, 0.3 for carbon emission minimization, 0.256 for employment rate maximization and 0.196 for development rate maximization. Afterward, in the second stage, a Multi-Objective Mixed Integer Linear Programming Model (MO-MILP) is developed to design the reverse logistics network and an application is performed in Turkey for validation. The model is solved for various scenarios including different quantities to be collected. Hence, it is obtained that the satisfaction degrees for employment and development objectives are 100% in all of the scenarios. However, the satisfaction degree of carbon emission minimization is around 96% and the less satisfied objective is the cost minimization having a satisfaction degree of 75% on average.

1. Introduction

There exists limited resource capacity in nature and because of the overpopulation in the world, these limited resources are depleted quickly. This case creates the need to seek some methods to obtain new raw materials and resources and conserve the existing ones. Additionally, with the spread of consumer society, waste rates have increased even more and become a global problem. This problem disrupts the human-ecosystem balance and reduces sustainable living standards. As a consequence of the cycle of these events, reverse logistics which includes the recovery of end-products by gaining value step by step term has emerged. Throughout the 1980s, the concept of reverse logistics was limited to the movement of the product from the customer to the manufacturer, as opposed to the primary flow. In 2001, Stock [1] defined reverse logistics as "the role of logistics in product returns, resource reduction, recovery, material substitution, materials reuse, waste disposal and incineration, repair and remanufacturing".

Today, in the world, the importance of reverse logistics applications has been realized by many countries. Reverse logistics not only provides cost advantages but also contributes to energy savings. It is observed that proper recovery of the materials minimizes the harmful influence on the environment and satisfies the requirement of raw material usage. In many researches and applications, it is stated that the reuse of papers in manufacturing decreases air pollution by between 74%–94%, water contamination by 35%, and water usage by 45% [2]. Additionally, savings from the recovery of glass products decrease energy consumption by 25%, air pollution by 20%, mine dumps by 80% and water consumption by 50% [3]. On the other hand, aluminum recovery provides savings in energy consumption by 95%, in air pollution by 90%, in water contamination by 97%, and in stack gas pollutant emission by 99% [3].

The amount of waste generated each year in the world is approximately 2 gigatons [4]. Nearly 1.2 gigatons of these wastes can be recycled. If most of these wastes were recycled instead of disposed of, 10% of the world's electricity consumption can be met by the recovered energy from this recycling process. The annual turnover of the world recycling industry is approximately 475 billion dollars and the annual turnover of the world waste-to-energy production sector is 13.6 billion dollars [5]. Whereas,

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in Turkey, approximately 35 megatons of industrial waste are collected each year and the economical magnitude of Turkey's recycling industry is nearly 5 billion dollars annually [5].

The recyclable waste generated only from residential areas of Turkey is about 6 megatons [6]. Unfortunately, due to the lack of proper organizational and economical structure in Turkey, nearly 5 megatons of these wastes are buried without entering any recycling or recovering process [6]. The deficiency of having the proper structure for recycling costs 2.25 billion TL to Turkey, without including the impact of environmental damage of buried wastes [5]. This deficiency can be handled from two different perspectives: reverse supply chain management and technical sufficiency. The transportation of the recyclable used products from the points of consumption to the collection points for recycling evolved with the incorporation of recovery activities such as reuse and remanufacturing has become an integrated approach what is known as reverse supply chain management. In reverse logistics, effectual management of these operations can be achieved by creating a network design. On the other side, technical sufficiency depends on the development of engineering competence.

Nowadays, the demand for proper disposal of non-reusable and hazardous materials has increased more than ever with growing awareness in a limited resource environment. According to World Bank Data [6], global waste is expected to grow to 3.40 billion tons by 2050. Hence, consumers and authorities put pressure on manufacturers about the recycling or disposal of the wastes resulting from consumption. In addition to these environmental and cost-based opportunities for businesses, reverse logistics is now obligatory with legal regulations valid in many countries. The purpose of these regulations is to realize the use of the material for a longer period with reuse and recycling, to learn how the use of materials and products can be more effective, and to ensure the intensity of the products to nature with product design [7].

The remainder of this paper is organized as follows: Part 2 includes the research motivation and contributions. In part 3, the relevant literature about waste management is given. Part 4 provides methodological details about the proposed model. In part 5, the proposed model is presented with the application of the case in Turkey. Then, in part 6, the results and discussions are provided with the comparative and sensitivity analyses. Finally, the conclusion is presented in part 7.

2. Research motivation and contributions

In this study, the recycling of waste batteries is determined as the focal point. Since the batteries contain both environmentally hazardous and recyclable substances, after valuable metal parts of the batteries are recovered, the remaining parts should be disposed of in a way that is not harmful to human health and the environment. In the last 15 years, the lithium-ion battery market has grown approximately 30 times [8]. According to the Environmental Protection Agency (EPA) [9], each year Americans throw away more than three billion batteries which are in turn about 180,000 tons of batteries. In 2021, Eurostat data [10] showed that around 205,000 tons of portable batteries and accumulators were put on the market (sales) in the EU, while around 100,000 tons were collected as recyclable waste. Breiter et al. [11] estimated that the demand is expected to grow by around 30 percent, a year globally by 2030, and the battery value chain is expected to increase by as much as ten times between 2020 and 2030 to reach annual revenue as high as $410 billion. As can be seen from the published statistics, waste management of batteries increases its importance day by day, and it would not be wrong to say that batteries are too valuable to be thrown away.

The growing market and the accompanying circumstances have shown that there is a need for research on the reverse logistics network design of waste batteries. Although there are numerous studies about reverse logistics network designs of various items, the number of studies focusing directly on waste batteries is limited. Therefore, in this study, initially, literature is reviewed from a reverse logistic point of view, especially with the waste management of batteries focus and developed models are examined. Then, a model for waste batteries in Turkey is proposed and implemented in a case. In the study, objectives are determined considering the three main dimensions of sustainability. In this sense, cost minimization is determined for the economic dimension, minimization of carbon footprint is handled for the environmental dimension and finally, increases in employment and maximization of socio-economic development level are considered for the social dimension. It is thought that this study will contribute to the literature since multi-objective optimization focuses on both tangible and intangible factors. Another original point that the study presents is the integration of the spherical fuzzy analytic hierarchy process (SF-AHP) and multi-objective optimization model. Hence, in brief, it is thought that this study will contribute to the literature by providing the listed points;

- Multiple objectives including the various dimensions of sustainability are considered for the reverse logistics network design of waste batteries.
- A two-stage methodology including the spherical fuzzy analytic hierarchy process (SF-AHP) and multi-objective optimization model is developed.
- A comparative analysis with alternative multi-objective methods including preemptive goal programming and max–min methods is provided.
- A sensitivity analysis including various objective importance weights is performed.
- The reverse logistics network design of waste batteries in Turkey is performed under multiple objectives and scenarios.

3. Literature review

Waste management comprises six stages, generation, collection, transport, sorting processing, and disposal [12]. Although every step has its own dynamics, efficient planning of waste collection is essential since it directly affects the level of success. For this reason, in literature, studies mainly focused on the determination of the number of collection facilities and the locations of collection and disposal facilities.

In literature, researchers used different types of optimization models considering the changing dynamics of reverse logistic network design problems. In 1992, Alidi [13] constructed an integer goal programming model in order to minimize the cost and determine the optimal locations of treatment transfer stations, landfill and incineration plant sites, and the potential markets for recyclable materials. A presumptive example was used to examine the practicality of the constructed model and the results show that the model is very useful for planning and cost minimization of hazardous waste systems. Bloemhof-Ruwaard et al. [14] studied an environmental life-cycle optimization model for the European pulp and paper industry. They used a linear programming network flow model to find optimal configurations such as a distribution of pulp and paper production, and a level of recycling with the lowest environmental impact. Although simpler integer and linear programming algorithms were used in previous studies, recent literature reviews highlight the frequent use of mixed integer linear programming (MILP) in waste management.

In 2014, Ghiani et al. [15] conducted a comprehensive literature review about the use of operations research methodologies in solid waste management. They classified the literature into four major categories such as single-period location models, multi-period location models, location models integrating economic and social components and models with uncertainty. Their study also showed that the MILP approach is often preferred by researchers. In 2020, Batur et al. [16] also emphasized the usage of MILP in their literature review by presenting some studies using MILP in the last twenty years. Based on the literature review conducted in this study, some of the studies using MILP in different waste management problems are presented.

In 2005, Cebeci et al. [17] developed a recycling model by using MILP, in order to find the optimal flow of electrical and electronic equipment from the municipal collection points to the related facilities and minimize the overall costs. The study focused on a network design model of a household appliance manufacturer in Turkey. In 2011, Wolfer et al. [18] also studied waste electrical and electronic equipment in China and used the MILP to determine the physical configuration of a reverse logistics system. The model was applied to a case study for developing the optimal warehouse location in Greater Shanghai Area. Another analysis conducted by Köse [19] also used the MILP model and studied the recovery network design for used frying oils in Turkey. The objective was to maximize the difference between the revenue from secondary markets and the related costs. Demirel et al. [20] worked on a hybrid genetic algorithm for multistage integrated logistics network optimization. The aim was to decide the necessary number and the locations of the plants with the minimum cost. They have generated a multi-product MILP model for the logistics network design based on a heuristic approach with linear programming. The results of the different scenarios were obtained by using GAMS-CPLEX. Utku and Erol [21] developed a single objective multi-product mixed integer programming model for hazardous waste management problems. In the model, they specifically focused on the location selection of facilities considering the routing of hazardous waste. The proposed model was applied to the Marmara Region of Turkey and provided locations for facilities considering the type and amount of hazardous waste.

In most of the studies in the literature, it is aimed to model real-life constraints in more detail by establishing multi-objective models. List and Mirchandani [22] developed a multi-objective model for making routing decisions, for either material or waste shipments, and siting decisions for waste treatment facilities. Risk, cost, and risk equity were considered jointly in a multi-objective framework. Giannikos [23] also used a multi-objective model for locating disposal or treatment facilities and transporting hazardous waste along the links of a transportation network. Four objectives were considered in the study as total operating cost, total perceived risk, risk and disutility caused by the operation of the treatment facilities. Boyer et al. [24] focused on industrial hazardous waste and developed a bi-objective mixed integer programming model for location and routing problems. Minimization of total cost and transportation risks were determined as two main objectives. Samanlioglu [25] developed a mixed-integer model for location routing model and considered three objectives as minimization of total cost, transportation risk and total risk for the population. The proposed model was implemented in the Marmara Region of Turkey and 41 candidate sites were considered with an assumption that these facilities might simultaneously be generation, treatment, disposal and recycling centers. Zhao et al. [26] also focused on the same three objectives by using a multi-objective MILP model. The structure of the problem that Zhao et al. [26] focused on was a network design problem rather than the location-routing problem. In the study, multiple types of hazardous waste, waste facility and treatment technology were considered and node capacity, link capacity and comparability requirements were modeled simultaneously. Yu and Solvang [27] also improved a mathematical formulation based on a multi-objective mixed integer programming approach for the location-routing problem of hazardous waste management. In their model, system operating costs and risk were considered as two critical factors. Habibi et al. [28] used a multi-objective robust optimization model for site-selection of municipal solid waste in Tehran. Yilmaz et al. [29] focused on cost and risks of hazardous waste management operations and developed a multi-objective mixed integer model for location/routing problems. In their study, trade-offs between objectives were also considered and finally, a national hazardous waste management system for Turkey was proposed. In 2020, Bal and Badurdeen [30] used a multi-objective optimization model that considered social, environmental and economic criteria. Additionally, objectives were formulated considering relevant constraints. In 2021, Wang et al. [31] used multi objective mixed integer deterministic and stochastic models to design a reverse logistics network for household hazardous waste.

Some researchers used multi-criteria decision-making (MCDM) algorithms or their integrated versions with optimization models for the location selection of waste recycling plants. In 1996, Alidi [32] used a multi-objective optimization model based on the goal programming approach for the management of hazardous waste generated by the petrochemical industry. In the study, the analytic hierarchy process (AHP) was used to prioritize conflicting goals. Erkut et al. [33] presented a multi-criteria mixed-integer linear programming model to solve the location–allocation problem. Chauhan and Singh [34] used the MCDM methodology for selecting sustainable disposal locations for healthcare waste. Wichapa and Khokhajaikiat [35] focused on infection waste and developed a model for the minimization of multi-objective functions comprising the total cost and the final priority weight. In the study, fuzzy AHP, hybrid FAHP and goal programming were used to develop the model. In 2022, Sherif et al. [36] developed a three-stage hybrid methodology with the combination of ISM (Interpretive Structural Modeling), fuzzy AHP, and fuzzy COPRAS (Complex Proportional Assessment of Alternatives) methods to select the best sustainable location in India.

Although researchers used different optimization models for reverse logistic network design problems in different sectors with different constraints, there are common objectives. Pati et al. [37] developed a goal programming model for the paper recycling system in India and used a mixed integer goal programming (MIGP) model. In the model, multiple objectives with different priorities were developed such as minimizing the cost, increasing the recovery of wastepaper and product quality, and determining the optimal flow and locations. Rahmatian [38] worked on a multi-objective reverse logistics network design and analysis. A multi-objective facility location and allocation model was built by including three objectives: minimizing the overall cost, maximizing the collection of product returns and maximizing the recovery of the products. Mahmoudzadeh et al. [39] have designed a decentralized reverse logistics network for end-of-life vehicles from the third-party provider perspective. The goal was to minimize the overall cost of the network and the capacitated facility location–allocation problem formulated by MILP. Budak and Ustundag [40] worked on reverse logistics and network design for waste disposal in health institutions of Turkey. The aim was to minimize the overall cost and find the optimal collection and disposal system for wastes by using MILP. Merkisz-Guranowska [41] designed a recycling network regarding end-of-life vehicles. The objective of the model was to minimize

Table 1
Literature review for objectives of reverse logistics network design studies.

Objectives	Related literature
Cost minimization	[13,17,18,20,26,29,37,39–41,43,45]
Profit maximization	[19,46]
Minimization of environmental impact/carbon emission	[14,44]
Risk minimization	[22,25,47–50]
Time-related objectives	[47,51]

both network and transportation costs. Bing et al. [42] studied household plastic waste in the Netherlands and developed a MILP model that minimized transportation costs and environmental damage. In 2012, Kannan et al. [43] presented a study about a carbon footprint-based reverse logistics network design model. The objective was to minimize the overall cost and carbon emissions. Yu and Solvang [44] presented an article about a general reverse logistics network design model for product reuse and recycling with environmental considerations. The presented multi-objective mixed integer programming model had three objectives: minimizing the operation costs, minimizing the carbon emissions caused by the transportation and processing of the products and minimizing the waste of resources.

As can be seen from the literature, cost minimization is one of the main objectives of studies. In Table 1, a general review is presented. Constructed models were solved with different scenarios to make some inferences about the optimum solutions.

Similar solution methodologies have been used in studies focusing on battery recycling. Kannan et al. [43] studied a genetic algorithm approach for solving a closed-loop supply chain model for a case of battery recycling. The objective was to develop a supply chain network model for product returns. A genetic algorithm was applied to solve MILP. After that, the results obtained from the genetic algorithm were compared with GAMS optimization software to evaluate the performance of the methodology. Dönmez [46] has developed a MILP to design a reverse logistics network for waste batteries and implemented the model in Turkey. The objective was to maximize the profit and to design the reverse network of waste batteries. All models were programmed and implemented in GAMS optimization package and solved using the CPLEX solver. They have also conducted a sensitivity analysis for the changes in different parameters. Cingöz [52] studied the analysis and design of reverse logistics networks for waste collection in Mersin. The aim was to improve waste collection processes by using simulation and vehicle routing methods. Tadaros et al. [53] analyzed the needs and restrictions of reverse logistics of lithium-ion batteries in Sweden and developed a mixed integer programming model. The study aimed to provide a decision support tool for analyzing the input and optimizing the future of such a network. In 2023, Puviarasu et al. [54] used a hybrid MCDM model by integrating DEMATEL, best worst method and TOPSIS to select a location for a battery recycling plant. In the analyses, 26 sub-criteria were determined under socio-cultural, environmental, economic and policy and legal dimensions.

As a result of the literature review study, it is concluded that there is no study that utilizes MADM and MODM methods together for the network design of waste batteries. Hence, the main complexity of the proposed methodology is the synergistic use of these two approaches. Within the first approach, SF-AHP is selected among MADM methods depending on its strength and validated up-to-date applications [55,56] for determining the importance weights of the objectives. Within the second approach, the proposed multi-objective model is constructed based on the maximization of the total weighted satisfaction degree. The proposed model not only considers tangible factors but also intangible factors. The tangible factors consist of the costs such as transportation, storage, sorting, operation and disposal costs. Whereas, there are intangible factors that need to be considered while selecting the suitable locations for storage sites and recycling facilities such as carbon footprint, employment, socio-economic development level. After objectives are defined, weights are determined by using the spherical fuzzy analytical hierarchy process method. Weight data is used as input in solving the multi-objective model. Details of the proposed model and the parameters are presented in the following parts.

4. The proposed methodology

4.1. Framework of the proposed model

Batteries, which provide many conveniences in our lives, if released to nature after the end of their useful life, cause the heavy metals they contain to pass into the soil and surface waters. Hence, this causes environmental pollution first and then indirectly passes into the human body and harms human health. In addition, it has an economic value because it contains metals such as zinc, manganese, and iron at a high rate, while it also has a raw material value because it has minerals obtained from nature.

In the early 90s, it was realized that the foreign source dependency of the European Union's metal requirement was between 80% and 100% (86% Ni, 95% Co) and the batteries were the richest sources in terms of the metal contents after the primary metal blooms [57]. The energy consumed during the process of obtaining the metals from the metal blooms is much higher than the energy consumed in the recycling of the waste batteries. In the 2006/66/EC European Union directive, recycling of waste batteries was obligatory [57]. According to the 2007 data, there were approximately 160 kilotons of portable batteries released in the European Union countries. These released battery amounts contain a total of 110–115 kilotons of various metals. The market value of these metals is calculated between 50 and 100 million euros. As can be inferred from the above explanations, waste batteries are too valuable to be ignored [58].

In Turkey, the Portable Battery Manufacturers and Importers Association (TAP), is the only organization authorized by the Ministry of Environment and Urbanization to collect and dispose of waste batteries in a way that is not harmful to human health and environment. Until 2016, the rechargeable (secondary) part of these collected batteries (nearly 15%) was sent to European countries for recycling. The remaining parts (nearly 85%) were disposed of in landfills by TAP [59]. In May 2016, the first Waste Battery Recycling Facility was established by the Marmara Research Center (MAM) of the Scientific and Technological Research Council of Turkey (TUBITAK). It is aimed to collect 700 tons of batteries for the related year and is expected to prevent their damage to the environment and human health as well as to provide economic benefits by recycling zinc carbon, alkali and nickel-cadmium batteries which are nearly 90% of the total waste batteries.

Regarding the establishment of the first waste battery recycling facility in Turkey and the increasing trend in the world, it is certain that there is a need of making research about the reverse logistics network design of waste batteries. In this regard, a methodology whose main steps are presented in Fig. 1,

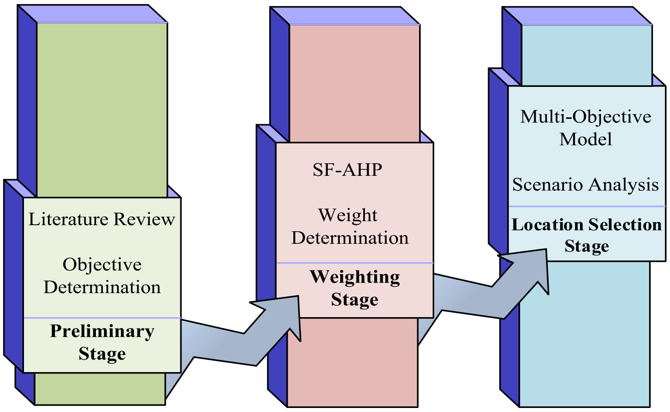


Fig. 1. The main stages of the proposed methodology.

is proposed in this research. As an initial step, the literature is reviewed and objectives are determined in Part 3. According to the conducted analysis, the proposed model is designed in a multi-objective structure, which not only considers tangible factors but also intangible factors. In the second step, weights are calculated using the SF-AHP method for the determined objectives. Preliminaries of the SF-AHP methodology are given in Part 4.2., and the detailed steps for the application of the method are given in Fig. 2. Finally, an MO-MILP model is developed for location selection. Detailed explanations about the parameters, variables, constraints and objective functions for the proposed model are presented in Part 4.3. The proposed model has been applied to the network design of waste batteries in Turkey, step by step in Part 5. In this regard, the problem is defined in Part 5.1, collected data is provided in Part 5.2 and the application of the proposed model is presented in Part 5.3.

4.2. SF-AHP

The AHP method proposed by Saaty [60] is one of the most frequently used multi-criteria decision making techniques in the literature. The method has a simple hierarchical structure, as well as provides the opportunity to evaluate the qualitative and quantitative criteria together by giving priority to the decision-makers. Basically, the AHP method aims to quantify the relative priorities for a given set of alternatives based on the binary judgments of the decision-makers.

However, in most real-life problems, the evaluations provided by the decision-makers fall short due to time pressure, skill and attention of the decision-makers. Moreover, classical AHP methods may be lacking in dealing with uncertainty and ambiguity in problems. In order to overcome this deficiency, studies that started with classical fuzzy sets [61] have been developed over time, followed by intuitive fuzzy sets [62], neutrosophic fuzzy sets [63] and hesitant fuzzy sets [64] versions have been suggested. More recently, "Spherical Fuzzy Sets (SF)" have been introduced as a synthesis of Pythagorean fuzzy sets [65] and Neutrosophic set theories [63] by Kutlu-Gündoğdu and Kahraman [66] with the idea that decision-makers can generalize different types of fuzzy sets. While membership functions of Pythagorean fuzzy sets are defined by membership, non-membership and hesitation parameters, membership functions of Neutrosophic fuzzy sets consist of truth, inaccuracy and uncertainty parameters. Spherical fuzzy (SF) sets are also able to generalize different types of fuzzy sets by defining a membership function on a spherical surface [66].

The membership function of an SF set is defined by three parameters, as membership degree ($\mu_{\tilde{A}_S}(x)$), non-membership degree ($\nu_{\tilde{A}_S}(x)$) and hesitation degree ($\pi_{\tilde{A}_S}(x)$). Each of these parameters can independently take a value between 0 and 1, and the sum of the squares of the values is at most 1.

In U_1 universal set, an SF set $\tilde{A}_S$ a is defined as $\tilde{A}_S = \left\{x, \left(\mu_{\tilde{A}_S}(x), \nu_{\tilde{A}_S}(x), \pi_{\tilde{A}_S}(x)\right) | x \in U_1\right\}$ and $\mu_{\tilde{A}_S}(x) : U_1 \rightarrow [0,1]$, $\nu_{\tilde{A}_S}(x) : U_1 \rightarrow [0,1]$, $\pi_{\tilde{A}_S}(x) : U_1 \rightarrow [0,1]\ \forall x \in U_1; 0 \leq \mu^2_{\tilde{A}_S}(x) + \nu^2_{\tilde{A}_S}(x) + \pi^2_{\tilde{A}_S}(x) \leq 1$. The basic arithmetic operations of SF sets such as union, intersection, addition, product and exponential value were defined by Kutlu-Gündoğdu and Kahraman [66]. In this regard, the basic arithmetic operations of two SF sets $\tilde{A}_S = (\mu_{\tilde{A}_S}, \nu_{\tilde{A}_S}, \pi_{\tilde{A}_S})$ and $\tilde{B}_S = (\mu_{\tilde{B}_S}, \nu_{\tilde{B}_S}, \pi_{\tilde{B}_S})$ are defined in Eqs. (1)–(6).

- Union;

$$\tilde{A}_S \cup \tilde{B}_S = \Bigg\{ max\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\}, min\left\{\nu_{\tilde{A}_S}, \nu_{\tilde{B}_S}\right\}, \\ min\left\{\left[1 - \left(\left(max\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\}\right)^2 + \left(min\left\{\nu_{\tilde{A}_S}, \nu_{\tilde{B}_S}\right\}\right)^2\right)\right]^{0.5}, \\ max\left\{\pi_{\tilde{A}_S}, \pi_{\tilde{B}_S}\right\}\right\}\Bigg\} \tag{1}$$

- Intersection;

$$\tilde{A}_S \cap \tilde{B}_S = \Bigg\{ min\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\}, max\left\{\nu_{\tilde{A}_S}, \nu_{\tilde{B}_S}\right\}, \\ max\left\{\left[1 - \left(\left(min\left\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\right\}\right)^2 + \left(max\left\{\nu_{\tilde{A}_S}, \nu_{\tilde{B}_S}\right\}\right)^2\right)\right]^{0.5}, \\ min\left\{\pi_{\tilde{A}_S}, \pi_{\tilde{B}_S}\right\}\right\}\Bigg\} \tag{2}$$

- Product;

$$\tilde{A}_S + \tilde{B}_S = \Bigg\{\left(\mu^2_{\tilde{A}_S} + \mu^2_{\tilde{B}_S} - \mu^2_{\tilde{A}_S}\mu^2_{\tilde{B}_S}\right)^{0.5}, \nu^2_{\tilde{A}_S}\nu^2_{\tilde{B}_S}, \Bigg(\left(1 - \mu^2_{\tilde{B}_S}\right)\pi^2_{\tilde{A}_S} \\ + \left(1 - \mu^2_{\tilde{A}_S}\right)\pi^2_{\tilde{B}_S} - \pi^2_{\tilde{A}_S}\pi^2_{\tilde{B}_S}\Bigg)^{0.5}\Bigg\} \tag{3}$$

- Multiplication of two sets ($\tilde{A}_S \times \tilde{B}_S$);

$$\tilde{A}_S \times \tilde{B}_S = \Bigg\{\mu_{\tilde{A}_S}\mu_{\tilde{B}_S}, \left(\nu^2_{\tilde{A}_S} + \nu^2_{\tilde{B}_S} - \nu^2_{\tilde{A}_S}\nu^2_{\tilde{B}_S}\right)^{0.5}, \Bigg(\left(1 - \nu^2_{\tilde{B}_S}\right)\pi^2_{\tilde{A}_S} \\ + \left(1 - \nu^2_{\tilde{A}_S}\right)\pi^2_{\tilde{B}_S} - \pi^2_{\tilde{A}_S}\pi^2_{\tilde{B}_S}\Bigg)^{0.5}\Bigg\} \tag{4}$$

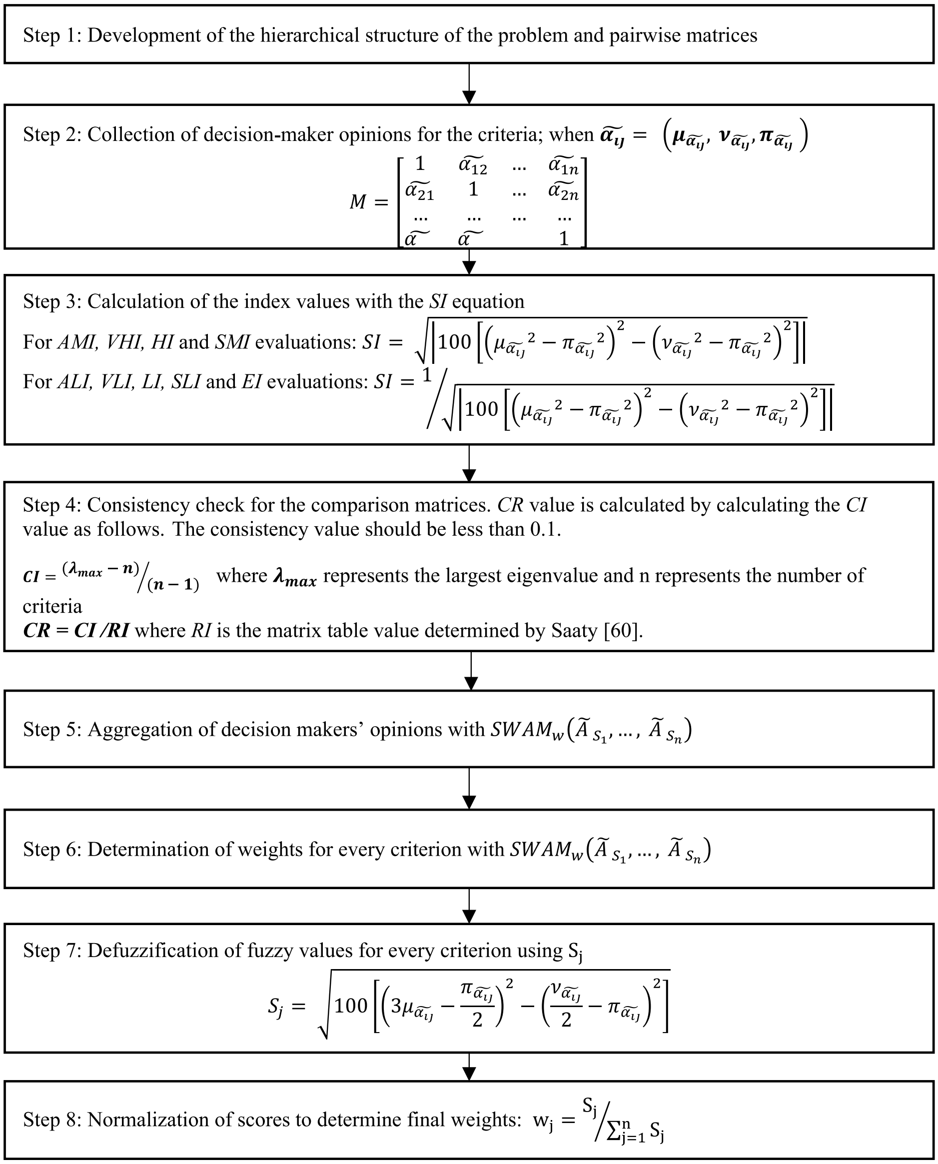
- Multiplication of a set and parameter ($\tilde{A}_S \times \lambda$)

$$\lambda \times \tilde{A}_S = \Bigg\{\left(1 - \left(1 - \mu^2_{\tilde{A}_S}\right)^{\lambda}\right)^{0.5}, \nu^{\lambda}_{\tilde{A}_S}, \Bigg(\left(1 - \mu^2_{\tilde{A}_S}\right)^{\lambda} \\ - \left(1 - \mu^2_{\tilde{A}_S} - \pi^2_{\tilde{A}_S}\right)^{\lambda}\Bigg)^{0.5}\Bigg\} \tag{5}$$

- Exponential value of set $\tilde{A}_S$ with parameter $\lambda > 0$

$$\tilde{A}^{\lambda}_S = \Bigg\{\mu^{\lambda}_{\tilde{A}_S}, \left(1 - \left(1 - \nu^2_{\tilde{A}_S}\right)^{\lambda}\right)^{0.5}, \Bigg(\left(1 - \nu^2_{\tilde{A}_S}\right)^{\lambda} \\ - \left(1 - \nu^2_{\tilde{A}_S} - \pi^2_{\tilde{A}_S}\right)^{\lambda}\Bigg)^{0.5}\Bigg\} \tag{6}$$

In addition to basic arithmetic operations, the following operations indicated in Eqs. (7) and (8) are also used for SF sets. In this



Step 1: Development of the hierarchical structure of the problem and pairwise matrices

Step 2: Collection of decision-maker opinions for the criteria; when $\boldsymbol{\widetilde{\alpha_{\imath\jmath}}} = \left(\boldsymbol{\mu}_{\widetilde{\alpha_{\imath\jmath}}}, \boldsymbol{\nu}_{\widetilde{\alpha_{\imath\jmath}}}, \boldsymbol{\pi}_{\widetilde{\alpha_{\imath\jmath}}}\right)$

$$M = \begin{bmatrix} 1 & \widetilde{\alpha_{12}} & \dots & \widetilde{\alpha_{1n}} \\ \widetilde{\alpha_{21}} & 1 & \dots & \widetilde{\alpha_{2n}} \\ \dots & \dots & \dots & \dots \\ \widetilde{\alpha} & \widetilde{\alpha} & & 1 \end{bmatrix}$$

Step 3: Calculation of the index values with the *SI* equation

For *AMI, VHI, HI* and *SMI* evaluations: $SI = \sqrt{\left|100\left[\left(\mu_{\widetilde{\alpha_{\imath\jmath}}}{}^2 - \pi_{\widetilde{\alpha_{\imath\jmath}}}{}^2\right)^2 - \left(\nu_{\widetilde{\alpha_{\imath\jmath}}}{}^2 - \pi_{\widetilde{\alpha_{\imath\jmath}}}{}^2\right)^2\right]\right|}$

For *ALI, VLI, LI, SLI* and *EI* evaluations: $SI = {}^{1}\Big/\sqrt{\left|100\left[\left(\mu_{\widetilde{\alpha_{\imath\jmath}}}{}^2 - \pi_{\widetilde{\alpha_{\imath\jmath}}}{}^2\right)^2 - \left(\nu_{\widetilde{\alpha_{\imath\jmath}}}{}^2 - \pi_{\widetilde{\alpha_{\imath\jmath}}}{}^2\right)^2\right]\right|}$

Step 4: Consistency check for the comparison matrices. *CR* value is calculated by calculating the *CI* value as follows. The consistency value should be less than 0.1.

$\boldsymbol{CI} = {}^{(\boldsymbol{\lambda_{max}} - \boldsymbol{n})}\big/_{(\boldsymbol{n}-\boldsymbol{1})}$ where $\boldsymbol{\lambda_{max}}$ represents the largest eigenvalue and n represents the number of criteria

CR* = *CI* /*RI where *RI* is the matrix table value determined by Saaty [60].

Step 5: Aggregation of decision makers' opinions with $SWAM_w(\tilde{A}_{S_1}, \dots, \tilde{A}_{S_n})$

Step 6: Determination of weights for every criterion with $SWAM_w(\tilde{A}_{S_1}, \dots, \tilde{A}_{S_n})$

Step 7: Defuzzification of fuzzy values for every criterion using $\mathrm{S_j}$

$$S_j = \sqrt{100\left[\left(3\mu_{\widetilde{\alpha_{\imath\jmath}}} - \frac{\pi_{\widetilde{\alpha_{\imath\jmath}}}}{2}\right)^2 - \left(\frac{\nu_{\widetilde{\alpha_{\imath\jmath}}}}{2} - \pi_{\widetilde{\alpha_{\imath\jmath}}}\right)^2\right]}$$

Step 8: Normalization of scores to determine final weights: $\mathrm{w_j} = {}^{\mathrm{S_j}}\big/_{\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{S_j}}$

Fig. 2. Steps of the SF-AHP method.

regard, when $w = (w_1, w_2, \dots, w_n)$ and $w_i \in [0, 1]$, $\sum_{i=1}^{n} w_i = 1$,

- Spherical weighted arithmetic mean *(SWAM)*

$$SWAM_w\left(\tilde{A}_{S_1}, \dots, \tilde{A}_{S_n}\right) = w_1\tilde{A}_{S_1} + w_2\tilde{A}_{S_2} + \dots + w_n\tilde{A}_{S_n}$$
$$= \left\{\left[1 - \prod_{i=1}^{n}\left(1 - \mu^2_{\tilde{A}_{S_i}}\right)^{w_i}\right]^{0.5}, \prod_{i=1}^{n}\nu^{w_i}_{\tilde{A}_{S_i}}, \left[\prod_{i=1}^{n}\left(1 - \mu^2_{\tilde{A}_{S_i}}\right)^{w_i} - \prod_{i=1}^{n}\left(1 - \mu^2_{\tilde{A}_{S_i}} - \pi^2_{\tilde{A}_{S_i}}\right)^{w_i}\right]^{0.5}\right\} \quad (7)$$

- Spherical weighted geometric mean *(SWGM)*

$$SWAM_w\left(\tilde{A}_{S_1}, \dots, \tilde{A}_{S_n}\right) = \tilde{A}_{S_1}^{w_1} + \tilde{A}_{S_2}^{w_2} + \dots + \tilde{A}_{S_n}^{w_n}$$
$$= \left\{\prod_{i=1}^{n}\mu^{w_i}_{\tilde{A}_{S_i}}, \left[1 - \prod_{i=1}^{n}\left(1 - \nu^2_{\tilde{A}_{S_i}}\right)^{w_i}\right]^{0.5}, \left[\prod_{i=1}^{n}\left(1 - \nu^2_{\tilde{A}_{S_i}}\right)^{w_i} - \prod_{i=1}^{n}\left(1 - \nu^2_{\tilde{A}_{S_i}} - \pi^2_{\tilde{A}_{S_i}}\right)^{w_i}\right]^{0.5}\right\} \quad (8)$$

SF sets are suggested in the literature as a useful tool to express uncertain information quite well. According to the literature review conducted by Ayyildiz and Taskin [67], although there are different decision-making methodologies that use SF sets, AHP is one of the most used methodologies in most of the publications. Within the scope of this study, the AHP method is used to determine the weights of the objectives utilized in the mathematical model. The application steps of the method are presented in Fig. 2. The obtained criteria weights are then used as inputs in the multi-objective optimization model of the problem, and the study is carried out afterward.

4.3. Proposed multi-objective model

After analyzing the related literature about the reverse network flow models, a multi-objective mixed integer linear programming model is developed by benefiting from the studies of Shih [68], Fleischmann [69], Kilic et al. [70] and Horasan

Table 2
Parameters of the model.

No	Parameter
1	The amount of waste batteries
2	Determination of the waste battery categories and their properties (*waste battery categories, unit transportation costs of the waste battery categories, waste battery material compositions, incomes of useful materials, transportation costs of the useful materials, disposal costs of hazardous materials, transportation costs of the hazardous materials*)
3	Specifications of the storage sites (*storage site capacities, annual fixed costs of the storage sites, storage site location sets*)
4	Specifications of the recycling facilities (*recycling facility capacities, annual fixed costs of the recycling facilities, sorting and operation costs of the waste battery categories, recycling facility location sets*)
5	Determination of the locations and capacities of secondary material markets
6	Determination of the locations and capacities of the landfill areas
7	Carbon footprint ratios
8	Unemployment ratios
9	Socio-economic development levels

Table 3
Subscripts and their descriptions.

Subscript	Description
o	: Objectives
c	: Waste battery categories
i	: Collection points
j	: Storage sites
k	: Recycling facilities
m	: Secondary material markets
l	: Landfill areas for the hazardous materials
u	: Useful materials which bring revenue
h	: Hazardous materials which cause cost

and Kilic [71]. The proposed mathematical model provides the values for the decision variables such as the types, numbers and locations of storage sites and recycling facilities; the quantity of batteries to be allocated to the storage sites and recycling facilities; the network flow of batteries through storage sites, recycling facilities, secondary material markets and landfill areas and finally the total weighted satisfaction degree and the satisfaction degree of each objective function.

While developing the mathematical model, the parameters and decision variables are clarified depending on the four objectives. Afterward, the objective functions and constraints are defined and the data about the parameter values are gathered from the provincial environment status reports, the Ministry of Environment and Urban Planning and the reports of the association of Portable Battery Manufacturers and Importers (TAP) [72], which is the only responsible organization for the collection of waste batteries in Turkey. However, since the first battery recycling facility was established in 2016, some parameter values were obtained either directly from different studies and articles or by making reasonable assumptions. Basically, the model parameters are determined as in Table 2.

All the values of the parameters are determined and used in the multi-objective mathematical model for maximizing the total weighted satisfaction degree. The nomenclatures used in the objective function are as in Tables 3–5.

In the proposed model four objectives are determined as follows:

$$\begin{aligned}
Minz_1 = {} & \sum_i \sum_j (q1_{ij} * d1_{ij} * tc) + \sum_j \sum_k (q2_{jk} * d2_{jk} * tc) \\
& + \sum_k \sum_m \sum_u (q3_{kmu} * d3_{km} * tc2_u) \\
& + \sum_k \sum_l \sum_h (q4_{klh} * d4_{kl} * tc3_h)\,\text{(Transportation cost)} \\
& + \sum_k \sum_c (qq2_{kc} * sc_{kc})\text{(Sorting cost at the recycling facility)} \\
& + \sum_k \sum_c (qq2_{kc} * oc_{kc})\text{(Operation cost at the recycling facilities)} \\
& + \sum_j \left(sfc_j * sb_j\right) + \sum_k (rfc_k * rb_k)\,\text{(Fixed costs of the storage} \\
& \text{sites, recycling facilities)} + \sum_k \sum_h (rawm2_{kh} * exp_h) \\
& \times \text{(hazardous materials disposal cost)} \\
& - \sum_k \sum_u (rawm1_{ku} * rev_u)\text{(Revenue from secondary markets)}
\end{aligned} \tag{9}$$

$$Min\,z_2 = \sum_k (q5_k * ce_k) \tag{10}$$

$$Max\,z_3 = \sum_k (q5_k * ur_k) \tag{11}$$

$$Max\,z_4 = \sum_k (q5_k * dc_k) \tag{12}$$

Within the first objective, it is aimed to provide an optimal flow of waste batteries from the collection points to the secondary material markets or final processing plants by minimizing the related costs. From an environmental perspective, the second objective is developed so as to minimize carbon footprint. However, opening a facility only to achieve economic or environmental objectives is not enough to achieve long-term success. It is important to consider the societal implications for facility opening decisions thus within the third and fourth objectives, it is aimed to determine the locations having the highest intangible capability for increasing the employment and maximizing the development levels. The model constraints consist of flow constraints (13)–(22), capacity constraints (23)–(28), maximum number limits for storage sites and recycling facilities (29)–(30), binary variables (31) and non-negative decision variables (32).

Flow Constraints

$$\sum_j q1_{ij} = a_i \quad \forall i \tag{13}$$

$$\sum_i q1_{ij} = b_j \quad \forall j \tag{14}$$

$$\sum_k q2_{jk} = b_j \quad \forall j \tag{15}$$

$$\sum_j \left(q2_{jk} * percentage_{kc}\right) = qq2_{kc} \quad \forall c, \forall k \tag{16}$$

$$\sum_c (qq2_{kc} * mat1_{cu} * rec_{ku}) = rawm1_{ku} \quad \forall k, \forall u \tag{17}$$

Table 4
Variables and their descriptions.

Variables	Description
$satobj_o$	: Satisfaction degree of objective "*o*"
z_o	: Value of objective "*o*"
w_o	: Importance weight of objective "*o*"
$TWSD$	: Total weighted satisfaction degree
$q1_{ij}$	: Quantity of waste battery transported from the collection point "*i*" to the storage site "*j*" (kg)
$q2_{jk}$	: Quantity of waste batteries transported from the storage site "*j*" to the recycling facility "*k*" (kg)
$q3_{kmu}$	: Quantity of useful material "*u*" transported from recycling facility "*k*" to the secondary material market "*m*" (kg)
$q4_{klh}$	: Quantity of hazardous material "h" transported from recycling facility "*k*" to the landfill area "*l*" (kg)
$q5_k$	: Quantity of waste battery at the recycling facility "*k*" (kg)
b_j	: Quantity of waste battery at the storage site "*j*" (kg)
$qq2_{kc}$	: Quantity of waste battery category "*c*" at the recycling facility "*k*" (kg)
sb_j	: Selection of the storage site "*j*" (1 or 0)
rb_k	: Selection of the recycling facility "*k*" (1 or 0)
$rawm1_{ku}$	: Quantity of useful material "*u*" at the recycling facility "*k*" (kg)
$rawm2_{kh}$	: Quantity of hazardous material "*h*" at the recycling facility "*k*" (kg)
$srawm1_{mu}$	: Quantity of the useful material "*u*" at the secondary material market "*m*" (kg)
$srawm2_{lh}$	: Quantity of the hazardous material "*h*" at the landfill area "*l*" (kg)

Table 5
Parameters and their descriptions.

Parameters	Description
max_o	: Maximum value of objective "*o*"
min_o	: Minimum value of objective "*o*"
a_i	: Quantity of waste battery at the collection point "*i*" (kg)
$d1_{ij}$	: Distance from the collection point "*i*" to the storage site "*j*" (km)
$d2_{jk}$	: Distance from the storage sites "*j*" to the recycling facility "*k*" (km)
$d3_{km}$	: Distance from the recycling facility "*k*" to the secondary material market "*m*" (km)
$d4_{kl}$	: Distance from the recycling facility "*k*" to the landfill area "*l*" (km)
tc	: Waste battery per km transportation cost ($/kg)
$tc2_u$	: "*u*" useful material transportation cost ($/kg*km)
$tc3_h$	: "*h*" hazardous material transportation cost ($/kg*km)
sc_{kc}	: Sorting cost of the waste battery category "*c*" at the recycling facility "*k*" ($/kg)
oc_{kc}	: Kg operation cost of waste battery category "*c*" at the recycling facility "*k*"($/kg)
$mat1_{cu}$	: Weight percentage of the useful material "*u*" in the waste battery category "*c*"
$mat2_{ch}$	: Weight percentage of the hazardous material "*h*" in the waste battery category "*c*"
rev_u	: Revenue of the useful material "*u*" ($/kg)
exp_h	: Cost of the hazardous material "*h*" ($/kg)
sfc_j	: Annual fixed cost of the storage site "*j*" ($)
rfc_k	: Annual fixed cost of the recycling facility "*k*" ($)
ce_k	: Carbon emission of the location where facility "*k*" exists
ur_k	: Unemployment rate of the location where facility "*k*" exists
dc_k	: Development category of the location where facility "*k*" exists (When the value is high, it means that it is less developed)
$minsca_j$	: Minimum capacity of the storage site "*j*" (kg)
$maxsca_j$	: Maximum capacity of the storage site "*j*" (kg)
$minrca_k$	: Minimum capacity of the recycling facility "*k*" (kg)
$maxrca_k$	: Maximum capacity of the recycling facility "*k*" (kg)
$recu_{ku}$	: The recycling rate of the useful material "*u*" at the recycling facility "*k*"
$maxsec_{mu}$	: Capacity of the secondary material market "*m*" (kg)
$maxland_{lh}$	: Capacity of the landfill area "*l*" (kg)
x	: Maximum number of the storage sites
y	: Maximum number of the recycling facilities
$percentage_{kc}$	: Waste battery category percentages at the recycling facility "*k*"

$$\sum_{m} q3_{kmu} = rawm1_{ku} \forall k, \quad \forall u \tag{18}$$

$$\sum_{c} (qq2_{kc} * mat2_{ch}) = rawm2_{kh} \quad \forall k, \forall h \tag{19}$$

$$\sum_{l} q4_{klh} = rawm2_{kh} \quad \forall k, \forall h \tag{20}$$

$$\sum_{k} q3_{kmu} = srawm1_{mu} \quad \forall m, \forall u \tag{21}$$

$$\sum_{k} q4_{klh} = srawm2_{lh} \quad \forall l, \forall h \tag{22}$$

Eq. (13) is the flow conservation at the collection points. Eqs. (14) and (15) are the flow conservations at the storage sites. Eq. (16) is the flow conservation at the recycling facilities. Eqs. (17) and (18) are the useful material conservations at the recycling facilities. Eqs. (19) and (20) are the hazardous material conservation at the recycling facilities. Eq. (21) is the flow conservation at the secondary material markets. Eq. (22) is the flow conservation at the landfill areas.

Capacity Constraints

$$b_j \geq minsca_j * sb_j \quad \forall j \tag{23}$$

$$b_j \leq maxsca_j * sb_j \quad \forall j \tag{24}$$

$$\sum_c qq2_{kc} \geq minrca_k * rb_k \quad \forall k \tag{25}$$

$$\sum_c qq2_{kc} \leq maxrca_k * rb_k \quad \forall k \tag{26}$$

$$srawm1_{mu} \leq maxsec_{mu} \quad \forall m, \forall u \tag{27}$$

$$srawm2_{lh} \leq maxland_{lh} \quad \forall l, \forall h \tag{28}$$

Eqs. (23) and (24) are the minimum and maximum storage site capacities. Eqs. (25) and (26) are the minimum and maximum recycling facility capacities. Eq. (27) is the capacity constraint for the secondary material markets. Eq. (28) is the capacity constraint for the landfill areas.

Maximum Number Limit of Storage Sites and Recycling Facilities

$$\sum_j sb_j \leq x \tag{29}$$

$$\sum_k rb_k \leq y \tag{30}$$

Eq. (29) is the maximum number limit for the storage sites and Eq. (30) is the maximum number limit for the recycling facilities.

0/1 binary variables

$$sb, rb \in \{0,\ 1\} \tag{31}$$

Non-negative decision variables

$$Others \geq 0 \tag{32}$$

The mathematical model is solved for each objective individually to find the maximum and minimum values. Afterward, the mathematical model is solved for the maximization of the total weighted satisfaction degree (TWSD) indicated in Eq. (33) by adding constraints 34–41 to the model. The importance weight parameter (w_o) is obtained from the first stage of the proposed methodology.

$$MaxTWSD = \sum_o (satobj_o * w_o) \tag{33}$$

Objective Function Values

$$\begin{aligned} z_1 = &\sum_i \sum_j (q1_{ij} * d1_{ij} * tc) + \sum_j \sum_k (q2_{jk} * d2_{jk} * tc) \\ &+ \sum_k \sum_m \sum_u (q3_{kmu} * d3_{km} * tc2_u) \\ &+ \sum_k \sum_l \sum_h (q4_{klh} * d4_{kl} * tc3_h) + \sum_k \sum_c (qq2_{kc} * sc_{kc}) \\ &+ \sum_k \sum_c (qq2_{kc} * oc_{kc}) + \sum_j \left(sfc_j * sb_j\right) + \sum_k (rfc_k * rb_k) \\ &+ \sum_k \sum_h (rawm2_{kh} * exp_h) - \sum_k \sum_u (rawm1_{ku} * rev_u) \end{aligned} \tag{34}$$

$$z_2 = \sum_k (q5_k * ce_k) \tag{35}$$

$$z_3 = \sum_k (q5_k * ur_k) \tag{36}$$

$$z_4 = \sum_k (q5_k * dc_k) \tag{37}$$

Objective Satisfaction Degrees

$$satobj_1 = (max_1 - z_1)/(max_1 - min_1) \tag{38}$$

$$satobj_2 = (max_2 - z_2)/(max_2 - min_2) \tag{39}$$

$$satobj_3 = (z_3 - min_3)/(max_3 - min_3) \tag{40}$$

$$satobj_4 = (z_4 - min_4)/(max_4 - min_4) \tag{41}$$

5. Reverse logistics network design of waste batteries in Turkey

The proposed methodology explained in detail in Part 4 is applied to a case study focusing on the network design of waste batteries in Turkey. In the following sections, all application steps are presented, starting with the definition of the problem and the collection of data for the relevant parameters. Afterward, in part 5.3., the implementation of the proposed model is presented.

5.1. Problem definition

A battery is a device that is used for the storage of chemical energy and it enables the transformation of this energy into electricity. A battery basically consists of a negative electrode (cathode), a positive electrode (anode), and an electrolyte [73]. Additionally, separators and protective outer covering are also used in order to physically separate these three components from each other and to increase mechanical endurance. Battery types are formed by the differentiation of electrodes (anode and cathode) and electrolyte [74].

Portable batteries are batteries that are not in the industrial or automotive category, which can be easily carried from one location to another (usually not exceeding 1–2 kilograms), and have a sealed structure (does not penetrate air, gas, water or other liquids to inside or outside) [57]. They are used in devices such as mobile phones, satellites, calculators, military radios, radios, toys, small house appliances and clocks. Portable batteries can be examined in two categories as wet cell batteries and dry cell batteries. Wet cell batteries are also known as lead–acid batteries. Dry cell batteries, on the other hand, can be separated into two groups: rechargeable batteries (secondary) and non-rechargeable batteries (primary) [75]. In this study, dry cell batteries (primary and secondary) are examined.

5.2. Data collection

Determination of the model parameters is very significant to obtain correct results from the model to be constructed. Since the exact amounts and related transportation and disposal costs of the waste batteries in Turkey were not recorded accurately, the provincial environment status reports and special waste statistics of the Ministry of Environment and Urban Planning as well as the reports of the TAP [72], which is the only responsible for the collection of the waste batteries, have been used in this study. In other respect, there is no information about the waste battery recycling facilities in Turkey, since the first battery recycling facility was established in 2016. Therefore, some of the necessary information is obtained either directly from different studies and articles or by making reasonable assumptions.

Table 6
Socio-economic development groups of the provinces in Turkey.

First-level developed provinces	Second-level developed provinces	Third-level developed provinces	Fourth-level developed provinces	Fifth-level developed provinces	Sixth-level developed provinces
İstanbul	Tekirdağ	Balıkesir	Rize	Sinop	Diyarbakır
Ankara	Denizli	Manisa	Düzce	Giresun	Kars
İzmir	Bolu	Mersin	Nevşehir	Osmaniye	Iğdır
Kocaeli	Edirne	Uşak	Amasya	Çankırı	Batman
Antalya	Yalova	Burdur	Kütahya	Aksaray	Ardahan
Bursa	Çanakkale	Bilecik	Elazığ	Niğde	Bingöl
Eskişehir	Kırklareli	Karabük	Kırşehir	Tokat	Şanlıurfa
Muğla	Adana	Zonguldak	Kırıkkale	Tunceli	Mardin
	Kayseri	Gaziantep	Malatya	Erzurum	Van
	Sakarya	Trabzon	Afyon	Kahramanmaraş	Bitlis
	Aydın	Karaman	Artvin	Ordu	Siirt
	Konya	Samsun	Erzincan	Gümüşhane	Şırnak
	Isparta		Hatay	Kilis	Ağrı
			Kastamonu	Bayburt	Hakkari
			Bartın	Yozgat	Muş
			Sivas	Adıyaman	
			Çorum		

5.2.1. *The amount of waste batteries*

Since there had been no waste battery recycling system in Turkey until 2016, collection details of the waste battery data were ignored and not recorded properly. The primary goal was to collect as many waste batteries as possible to decrease their harmful effects on the environment. In this study, it is assumed that each of Turkey's 81 provinces has one waste battery collection point. In order to estimate the future collection amounts and trends, the related regression equation is found by using the waste battery collection data obtained from TAP reports [72] and TAP's annual news [57]. Since there is uncertainty in the exact waste battery collection amounts for 81 provinces, this uncertainty is tried to be handled with different total collection amounts that are used in the scenarios.

In the study, it is considered that the expected amount of waste batteries to be collected is closely related to the socio-economic development (i.e income, demography, education and environmental sustainability) and population of each province. In Socio-Economic Development Index research (SEGE), Turkey's provinces are divided into six groups according to their socio-economic developments [76]. These levels are shown in Table 6.

Regression analysis is applied based on the existing data and the annual collection quantities are obtained as 1180 tons, 1448 tons and 1717 tons for the years 2023, 2028 and 2033, respectively and these are distributed to the cities.

On the other hand, for the distribution of the battery collection amounts on a category basis, battery sales percentages in Europe published by TAP [72] are used. These percentages are 17.5% for zinc-carbon, 46% for Alkaline, 7.5% for nickel-cadmium, 10.5% for nickel-metal hydride, 6% for lithium-ion, 7% for lithium and 5.5% for button cells. In the light of this information, battery category amounts, which are obtained after sorting operation, are calculated in scenarios.

5.2.2. *Determination of the waste battery categories and their properties*

Determination of the waste battery categories: The waste batteries, which come as mixed to the recycling facility, are firstly classified into seven categories according to their sizes and then their contents. These are Zinc-carbon, Alkaline, Nickel-cadmium, Nickel-metal hydride, Lithium-ion, Lithium and button cell (Mercury-oxide, Silver-oxide, Copper-oxide and Zinc-air) batteries.

Determination of the unit transportation costs of the waste battery categories: By considering, the model and size of the existing waste battery transportation vehicles, the carrying capacity is determined as approximately 1.4 tons and 11.7 cubic meters. Since there is no data available for the waste battery transportation costs, based on the data in the existing transport sector, $1 is taken as the per kilometer transportation cost for a truck that has a capacity of 1 ton. Since the average weights and volumes of the waste battery categories are approximately the same, for all categories kilometer transportation cost of a truck is taken as $0.001 per kilogram.

Determination of the waste battery material compositions: Material composition is important in network design as the value of the secondary market for each material is different. In this study, waste battery material compositions are given on a category basis. Category compositions vary according to the size and manufacturer of the batteries. In this regard, the average material composition of batteries is presented as follows [72];

- For Zinc-Carbon Batteries: 27% MnO_2; 23% Zn; 10% C; 18% H_2O; 5% $ZnCl/NH_4Cl$; 4% Fe; 13% Others (Plastic, Paper, etc.)
- For Alkaline Batteries: 37% MnO_2; 23% Fe; 16% Zn; 5% KOH; 4% C; 2% Brass; 13% Others (Plastic, Paper, etc.)
- For Nickel-Cadmium Batteries: 40% Fe; 22% Ni; 15% Cd; 5% Plastic; 2% KOH; 16% Others (Water, separator fiber, etc.)
- For Nickel-Metal Hydride Batteries: 35% Ni; 20% Fe; 10% Rare earth materials (lanthanides); 4% Co; 9% Plastic; 4% KOH; 1% Mn; 1% Zn; 16% Others (Water, separator fiber, etc.)
- For Lithium-Ion Batteries: 22% F3; 18% Co; 13% C; 5% Al; 3% Li; 11% Other metals; 28% Other (than metals)
- For Lithium Batteries: 30% MnO_2; 50% Fe, 7% Plastic; 6% Dimethoxyehane; 3% Li; 2% C; 2% Ni
- For Butten Cell (For this group, silver-oxide batteries are considered as a reference product): 42% Fe; 33% Ag_2O; 9% Zn; 4% Cu; 3% MnO_2; 2% H_2O; 2% Plastic; 2% Ni; 1% KOH; 0.5% C; 0.4% Hg; 1.1% Others

Determination of the incomes of useful materials: Waste batteries which are undergone physical and chemical processes in recycling facilities are separated by various materials. Some of these materials are useful materials that generate income from the secondary material markets. Incomes per kilogram for these materials are listed in Table 7.

Determination of the transportation costs of the useful materials: In order to transfer the useful materials to the secondary material markets, transportation costs per kg have to be determined. By considering the model and size of the existing waste battery transportation vehicles, $1 is taken as the per kilometer transportation cost for a truck that has a capacity of 1 ton. In this

Table 7
Incomes of useful materials ($/kg).

Useful material	Income ($/kg)	Useful material	Income ($/kg)
Mn (MnO_2)	2.16	Al	1.11
Zn	2.39	Li	0.07
Fe	0.18	Ni	7.49
Cd	0.26	Brass	2.61
Co	0.12	Paper	0.16
Cu	4.20	Plastic	0.31

Table 8
Minimum and maximum annual capacities of the storage site types.

Storage site type	Maximum capacity (kg)	Minimum capacity (kg)
Small	30000	21000
Medium	80000	56000
Large	200000	140000

case, the transportation costs for all useful materials are taken as \$0.001/kg per kilometer.

Determination of the disposal costs of hazardous materials: Hazardous materials that are released after the chemical processes are disposed of in special facilities for certain prices. In 2022, the disposal cost of the hazardous materials according to the General Hazardous Waste unit is determined as \$1.8.

Determination of the transportation costs of the hazardous materials: In order to transfer the hazardous materials to the related facilities and landfill areas, transportation costs per kg have to be determined. By considering the model and size of the existing waste battery transportation vehicles, \$1 is taken as the per kilometer transportation cost for a truck that has a capacity of 1 ton. In this case, the transportation costs for all hazardous materials are taken as \$0.001/kg per kilometer.

5.2.3. Specifications of the storage sites

In the existing system, battery manufacturers and sellers consolidate their legal responsibilities under a common association named TAP. The TAP association gives its battery recycling responsibility to a recycling facility. It is assumed that this centralized management will be able to maintain in future systems. There are no systematic storage sites in the current system. One of the reasons for the construction of storage sites is that it is too costly to transport small quantities of waste batteries from 81 collection points to the recycling facilities, regularly. The other reason is waste batteries cannot be transported through cargo companies which do not have hazardous waste licenses because waste batteries are in the hazardous waste category. Due to these reasons, a systematic structure is created. This will reduce transportation costs and provide operational convenience.

Specifying the storage site capacities: Since the categories of a single product are handled, the capacity of the storage sites can be defined by the amount of the product. Three types of storage site capacities which are small, medium and large will be identified as the possible storage site locations. It is assumed that storage sites will be used with a minimum capacity of 70%. In this situation, a total of 99 storage site sets are created in 33 provinces. The minimum and maximum annual capacities of the storage site types are shown in Table 8.

Specifying the annual fixed costs of the storage sites: One of the important costs for the system is storage site fixed cost. The costs of building a storage site will be different for the different regions of Turkey. For this reason, three types of storage site definitions are made as West, Middle and East. For each type, land purchasing, office, storage site building, storage site supervisor, security officer, worker, forklift, IT hardware software, weighbridge, annual fixed energy cost and annual fixed office costs are determined as cost items. Annual fixed cost for the storage sites is calculated by summing depreciation expenses, annual fixed energy costs, annual fixed office costs and administrative costs. Depreciation periods are taken from the Revenue Administration Department [77].

Table 9
Annual fixed cost ($) of storage sites.

Storage site type	West	Middle	East
Small	\$29272	\$25590	\$22795
Medium	\$37597	\$33335	\$29813
Large	\$46532	\$41613	\$37318

Table 10
Minimum and maximum annual capacities of the recycling facility types.

Recycling facility type	Maximum capacity (kg)	Minimum capacity (kg)
Small	100000	80000
Medium	300000	240000
Large	600000	480000

Land purchasing costs vary according to the storage site types that are planned to be made in the west, middle and east. Every storage site should have an office. It is planned to have a 30 m^2 office in small type, a 50 m^2 office in medium type and a 90 m^2 office in large type storage sites. The storage site buildings will be constructed so that waste battery barrels are not affected by external factors. The annual fixed energy cost is considered as the sum of various cost items such as stock area lighting and environmental lighting which are not related to the waste battery amount. For the calculation of the annual fixed office costs, various fixed costs such as electricity, water, telephone, documentation and cleaning are considered. Administrative costs are based on storage site supervisor, security officer and worker expenses which are expected to be at least one in each storage site. The depreciation period is taken as 50 years for all cost items. There is no need for additional storage material as the waste batteries are collected in the barrels. At least one forklift, one weighbridge and IT hardware and software for the storage site supervisor are planned to be used in each storage site. The depreciation periods of the forklift, IT hardware–software and weighbridge are taken as 4, 3 and 7 years, respectively. In the light of this cost information, the expected annual fixed costs for the storage sites according to types and regions are calculated in Table 9.

5.2.4. Specifications of the recycling facilities

Current battery recycling technology in Turkey is capable to recycle every type of collected waste battery. As a result of the interviews, the existing battery recycling facility will begin to recycle all battery types over time. Therefore, it is assumed that existing and potential recycling facilities will have the technology to recycle all battery types. The annual capacity of the facilities is defined as kilograms.

Specifying the recycling facility capacities: The annual capacity of the existing recycling facility is 300,000 kilograms. Three types of recycling facility capacities which are small, medium and large are identified as the possible recycling facility locations. It is assumed that recycling facilities will be used with a minimum capacity of 80%. In this situation, a total of 97 recycling facility sets are created in 32 provinces. For Kocaeli, since there exists one recycling facility, additional recycling facility types are not defined. The minimum and maximum annual capacities for recycling facilities are shown in Table 10.

Specifying the annual fixed costs, sorting and operation costs of the recycling facilities: According to the obtained information, the

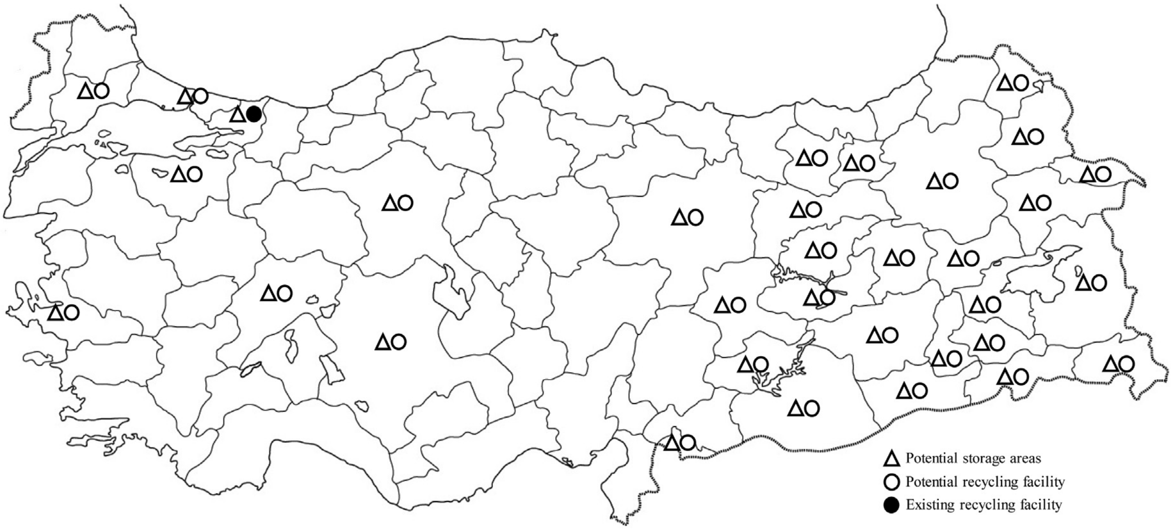


Fig. 3. Potential storage sites and recycling facility locations.

Table 11
Annual fixed cost ($) of recycling facilities.

Recycling facility type	West	Middle	East
Small	$28409	$22727	$19886
Medium	$42614	$36932	$34091
Large	$71023	$65341	$62500

depreciation period is taken as 50 years and when the construction cost, installing technology cost and the related equipment cost and other annual expenses are added, the annual fixed costs are determined. Sorting cost per kg and operation cost per kg are taken as \$0.142 and \$0.653 for all types of recycling facilities, respectively. These costs are taken as average values including all waste battery categories. Annual fixed costs, sorting costs and operation costs of the recycling facilities are shown in Table 11.

Specifying the recycling facility location sets: It is assumed that each of Turkey's 81 provinces has one waste battery collection point. There is one recycling facility in the current situation. The potential locations for the storage sites and recycling facilities are designated by considering supportive information sources.

With the 2021 decree, in order to reduce the development gap between the regions, Adıyaman, Ağrı, Ardahan, Batman, Bayburt, Bingöl, Bitlis, Diyarbakır, Elazığ, Erzincan, Erzurum, Gümüşhane, Hakkâri, Iğdır, Kars, Kilis, Malatya, Mardin, Muş, Siirt, Sivas, Şanlıurfa, Şırnak, Tunceli and Van provinces are stated as the attraction centers. Incentives such as free investment site support and interest-free investment loan support are given to these provinces [78]. Besides, significant incentives are offered to entrepreneurs who want to invest in the Organized Industrial Zones (OIZ). İstanbul, Kocaeli, Bursa, Tekirdağ, İzmir, Ankara and Konya, Afyonkarahisar provinces have the most organized industrial zones in Turkey. In this regard, potential storage sites and recycling facility locations have been determined and shown in Fig. 3.

5.2.5. Determination of the locations and capacities of secondary material markets

Useful materials coming from recycling facilities will be sent to the secondary material markets in order to obtain revenue. In this case, iron and manganese will be sent to Hatay (İskenderun), Zonguldak or Karabük. Copper will be sent to Samsun, Artvin (Murgul) or Diyarbakır (Ergani) and aluminum will be sent to Konya (Seydişehir) and Bursa. It is assumed that secondary material markets for other revenue-generating materials are in the organized industrial zones which are İstanbul, Bursa, Tekirdağ, İzmir, Kocaeli and Konya. There are no capacity restrictions for these markets.

5.2.6. Determination of the locations and capacities of the landfill areas

Hazardous materials obtained from chemical processes are sent to the special facilities and disposed of in a way that is not harmful to human health and the environment. There are no capacity restrictions for the landfill areas. The landfill area locations are determined as İstanbul, İzmir, Bursa and Kocaeli.

5.2.7. Carbon emission ratio calculation

Carbon emission basically points to the release of carbon amount into the atmosphere due to the reasons such as uncontrolled industrialization, greenhouse gas emissions, increasing population and urbanization. CO_2 emission reports indicate that Turkey has 5.32 tons of CO_2 emissions per capita with a total CO_2 emission amount of 449.7 million tons in 2021 [79]. Considering that the population of Turkey in 2021 was 84,680,273 according to TUIK data [80], it approximately corresponds to 450 million tons as indicated. In this study, carbon emission amounts are calculated based on the population of provinces in 2021 and used as input data. In the model, the lowest carbon emission is aimed to avoid dangerous environmental risks in terms of sustainability dimensions.

5.2.8. Unemployment ratio determination

Within the scope of labor statistics for 2021 [81], unemployment and unemployment rates on the basis of province groups are collected. According to the data, the region with the highest unemployment rate is TRC3 (Mardin, Batman, Şırnak, Siirt) with 29.8%, while the region with the lowest unemployment rate was TR82 (Kastamonu, Çankırı, Sinop) with 5.8% [81]. For selected provinces, the unemployment ratio is collected and directly used in the model. It is aimed to select the locations having the highest unemployment ratios so as to increase the employment rates by establishing a disposal facility.

Table 12
SF evaluation set based on a nine-point scale.
Source: Adapted from [67].

Definition	SF (9 point scale) $(\mu\ ;\ \nu;\ \pi)$	Score index *(SI)*
Absolutely High Importance-AHI	(0.9 ; 0.1 ; 0.1)	9
Very High Importance-VHI	(0.8 ; 0.2 ; 0.2)	7
High Importance-HI	(0.7 ; 0.3 ; 0.3)	5
Slightly more importance- SMI	(0.6 ; 0.4 ; 0.4)	3
Equal Importance-EI	(0.5 ; 0.5 ; 0.5)	1
Slightly low importance-SLI	(0.4 ; 0.6 ; 0.4)	1/3
Low Importance-LI	(0.3 ; 0.7 ; 0.3)	1/5
Very Low Importance-VLI	(0.2 ; 0.8 ; 0.2)	1/7
Absolutely Low Importance-ALI	(0.1 ; 0.9 ; 0.1)	1/9

Table 13
Aggregated opinions of six decision makers.

	CER			*UER*			*SEDL*			*C*		
	μ	ν	π	μ	ν	π	μ	ν	π	μ	ν	π
Carbon emission ratio (CER)	0.5	0.4	0.4	0.6	0.4	0.3	0.6	0.3	0.2	0.7	0.4	0.2
Unemployment ratio (UER)	0.4	0.6	0.3	0.55	0.4	0.4	0.6	0.5	0.3	0.5	0.3	0.2
Socio-economic development Level (SEDL)	0.4	0.6	0.3	0.36	0.5	0.3	0.5	0.4	0.4	0.4	0.5	0.2
Cost (C)	0.5	0.5	0.2	0.53	0.5	0.2	0.6	0.4	0.2	0.4	0.4	0.4

5.2.9. *Determination of socio-economic development level*

In Socio-Economic Development Index research (SEGE), Turkey's provinces are divided into six groups according to their socio-economic developments [76]. These levels are shown in Table 5. The first and second development levels indicate the most developed provinces, while the sixth level shows the provinces with the least developed level. In the model, this ranking is used as input data and maximization of the socio-economic development level is aimed.

5.3. *Implementation of the proposed model*

After the relevant data is collected for the parameters, weights for the objectives are determined in Part 5.3.1. by following the SF-AHP steps given in part 4.2. Finally, in part 5.3.2., the proposed MO-MILP model provided in part 4.3 is applied and the final solutions have been obtained.

5.3.1. *Weight determination with SF-AHP*

In the proposed model, four objectives are determined as mentioned in Part 4.3. and these are (i) minimization of the related costs, (ii) minimization of carbon footprint, (iii) maximization of employment level and (iv) maximization of the socio-economic development level. As an initial step of the proposed model, weights are calculated for objectives using SF-AHP methodology as presented in Fig. 2.

In this regard, firstly, the opinions of six decision makers who are experts in the related area are collected with a survey in which a pairwise matrix of determined objectives is created. Afterward, decision makers are asked to evaluate the importance of each objective function considering the other one with a given nine-point scale as presented in Table 12.

After opinions are collected, the consistency of each decision maker is tested as presented in Fig. 2 (Step 4). It is seen that for each decision maker, the consistency ratio is below 0.10, which is the desired level for the SF-AHP methodology. Then in step 5, the collected opinions of decision makers are aggregated with SWAM operator as defined in Eq. (7). In Table 13, the aggregated pairwise matrix is presented.

Aggregated opinions are used to determine the final weights for each objective. In this sense, the steps that are presented in Fig. 2 are followed, respectively. As a final result, weights are determined as **0.300; 0.256; 0.196; 0.248** for carbon footprint ratio, unemployment ratio, socio-economic level and cost, respectively. These weight data are then used as inputs in the proposed model's methodology as presented in Fig. 1.

5.3.2. *Application of the proposed MO-MILP model*

The mathematical model is run for each objective individually. Firstly, the minimum and maximum values for each objective function (Objective 1: Cost minimization, objective 2: Carbon emission minimization, objective 3: Employment rate maximization, and objective 4: Development rate maximization) are obtained as in Table 14.

Afterward, the importance weights of the objectives are used within the mathematical model. The obtained importance weights of the objectives in the first stage are 0.248, 0.3, 0.256 and 0.196, respectively. The model is solved by the LINGO program (Snapshots of the results are provided in Appendix Figs. A.1–A.3) and the satisfaction degrees for each objective and the total weighted satisfaction degree are obtained for all scenarios as in Table 15. Each scenario has different quantities to be collected for the years 2023 (1180 tons), 2028 (1448 tons) and 2033 (1717 tons). The satisfaction degrees for employment and development objectives are 100% in all of the scenarios. The satisfaction degree of carbon emission minimization is around 96% in all the scenarios. However, the less satisfied objective is the cost minimization, which has a satisfaction degree of 75% on average.

Finally, the selected storage areas and recycling facilities for all scenarios are obtained as in Table 16.

6. Results and discussions

The locations of storage areas and facilities are represented in Fig. 4 [82]. For the first scenario, where the total quantity to be collected is around 1180 tons, six locations for storage areas and three locations for recycling facilities are selected. The capacity usage rates for storage areas and recycling facilities are 90.73% and 86.67%, respectively.

On the other hand, for the second scenario, where the total quantity to be collected is around 1448 tons, eight locations for storage areas and four locations for recycling facilities are selected. The capacity usage rates for storage areas and recycling facilities are 90.54% and 80.72%, respectively. Finally, for the third scenario, where the total quantity to be collected is around 1717

Table 14
Minimum and maximum values of objectives for each scenario.

Objectives	Scenario 1		Scenario 2		Scenario 3	
	Min	Max	Min	Max	Min	Max
Objective 1	922794	5797377	1137825	7056670	1359660	8300505
Objective 2	3010436	81817510	3131020	92373740	3251604	101316200
Objective 3	8790566	30318440	10883910	38322720	12977250	46327000
Objective 4	1180082	5880492	1448682	7492092	1717282	9103692

Table 15
Objective satisfaction degrees for all scenarios.

Objective satisfaction degrees	Scenario 1	Scenario 2	Scenario 3
Objective 1	76.72%	73.16%	73.85%
Objective 2	96%	96.58%	94.91%
Objective 3	100%	100%	100%
Objective 4	100%	100%	100%
Total weighted satisfaction degree	93.03%	92.32%	91.99%

Table 16
Selected storage areas and recycling facilities for all scenarios.

Scenarios	Selected storage areas	Selected recycling facilities
Scenario 1	Diyarbakır (Type 3), Elazığ (Type 3), İstanbul (Type 3), Kocaeli (Type 3), Mardin (Types 2,3), Batman (Type 3)	Kocaeli, Mardin (Types 1,2), Batman (Type 3)
Scenario 2	Bitlis (Type 3), Erzincan (Type 3), İstanbul (Type 3), Kocaeli (Type 3), Malatya (Type 3), Mardin (Type 3), Şanlıurfa (Type 3), Şırnak (Type 3)	Kocaeli, Mardin (Type 2), Siirt (Type 3), Batman (Type 3)
Scenario 3	Adıyaman (Type 3), Bingöl (Type 3), İstanbul (Type 3), Kocaeli (Type 3), Mardin (Type 3), Tunceli (Type 3), Şanlıurfa (Type 3), Batman (Type 3), Şırnak (Type 3)	Kocaeli, Mardin (Type 3), Batman (Types 2, 3)

tons, nine locations for storage areas and three locations for recycling facilities are selected. The capacity usage rates for storage areas and recycling facilities are 95.40% and 94.05%, respectively.

Considering all the scenarios, the storage areas and recycling facilities are located in the northwest and southeast of Turkey. However, the density is higher in the southeast of Turkey. These results are consistent with the situation of Turkey's regions. Since the unemployment rate, development requirements are high and carbon emission levels are less in the southeast of Turkey, the cities in that region are selected by the model depending on the effects of the related three objectives.

Although there are significant efforts and various studies on reverse logistics network design, it is not easy to find an ideal method suitable for every case including different requirements, expectations and hence conflicting objectives to satisfy. Moreover, each specific case has its own dynamics and constraints. Therefore, considering the properties of the problem, it is important to determine the suitable methods to utilize in the methodology. Moreover, while proposing a methodology, the synergistic use of utilized methods also becomes very important. Accordingly, it is benefited from the synergy of two methods in this study. Based on the knowledge of the authors, it is the first time in the literature that a two-stage methodology including an MADM method in the first stage and an MODM model in the second stage are presented for the network design of waste batteries.

Firstly, the SF-AHP method is used to obtain the importance weights of the objectives. Then, these importance weights are used as inputs in the MO-MILP model. The reason of choosing SF-AHP among various MADM methods depends on its strength and validated up-to-date applications as explained in the previous sections. However, a sensitivity analysis is also performed to see the effect of different objective importance weights on the results. On the other hand, it is desired to maximize the total weighted satisfaction degree of objectives in the second stage. Since the aim is clear, an MO-MILP model is constructed for accomplishing this aim specifically. However, a comparative analysis is also performed to evaluate the results. Hence, the approach used within the methodology is supposed to shed light on academics dealing with similar types of problems.

In addition to the integrated synergistic use of these two approaches, the considered objectives also provide the dimensions of sustainability. Different from the generic studies including only cost within the reverse logistics network design models, local conditions under the sustainability perspective are also considered. Accordingly, considering the dimensions of sustainability, carbon emission minimization is added as an environmental dimension, and maximization of employment and development rates are used within the model as social dimensions of sustainability. Since the recycling of waste batteries in Turkey started in 2016, the system has had deficiencies and not running in the most efficient way. In accordance with this situation, various questions about the waste battery reverse logistics network design in Turkey are desired to be answered with this study. Hence, this study is supposed to guide practitioners who have multiple objectives within the design of reverse logistics networks. Moreover, governments and organizations can benefit from the proposed methodology and extend it for the use of other waste types.

6.1. Comparison of the proposed MO-MILP model with other multi-objective methods

In addition to the application of the proposed MO-MILP model, the related problem is also solved by two other techniques including goal programming (preemptive) and max–min methods. As stated in a recent literature review study by Karimi et al. [83], goal programming and max–min methods are the most frequently used two methods within all multi-objective optimization approaches. Hence, these two strong techniques are chosen for the comparative analysis depending on their usage frequency and validated applications in the literature.

The main goal of the proposed method is to maximize the total weighted satisfaction degree. Hence, the satisfaction degree of each objective obtained from each method is indicated in Table 17. It is concluded that the proposed method has the highest

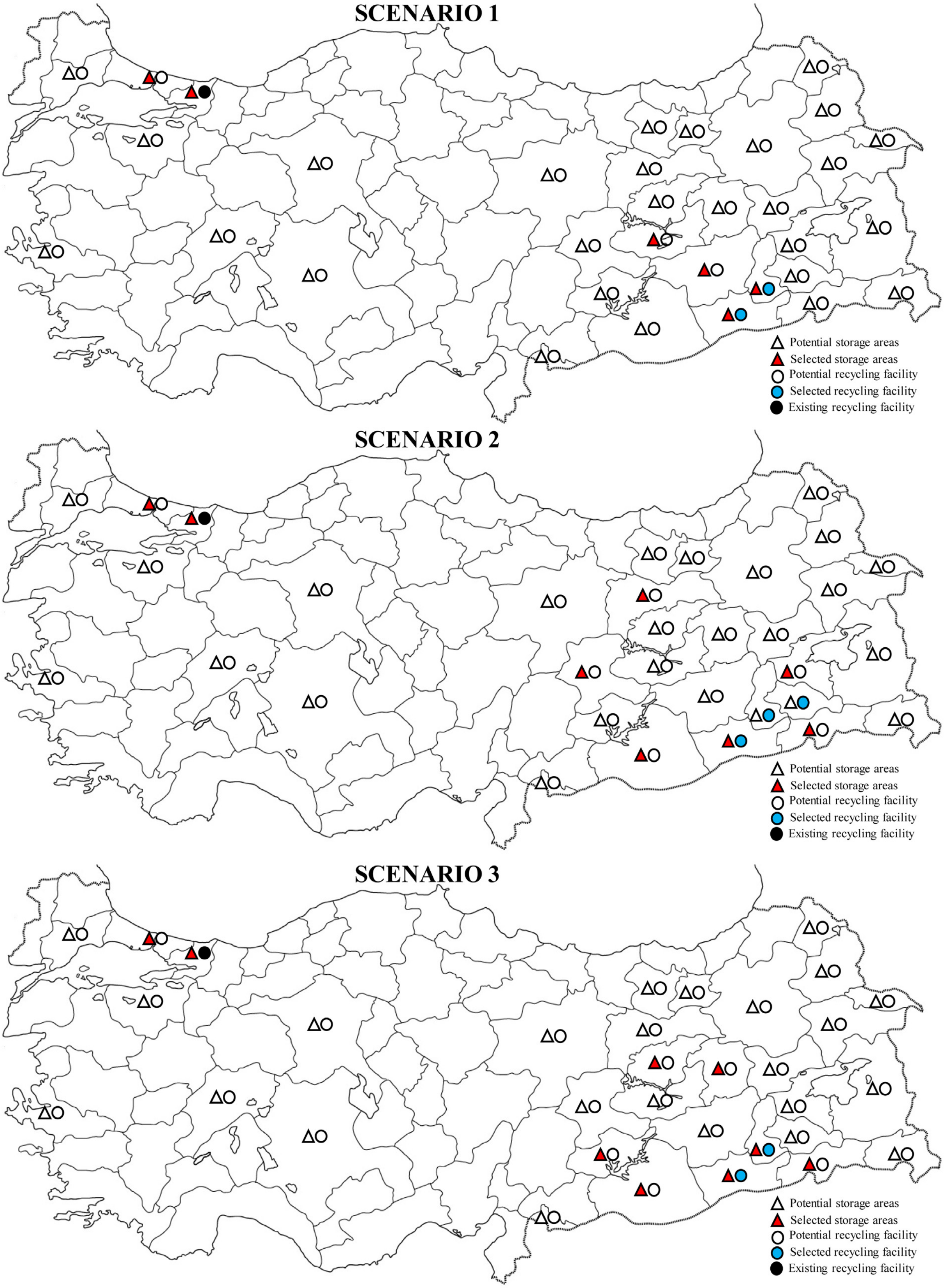


Fig. 4. The locations of the selected storage areas and recycling facilities for all scenarios.

Table 17
Comparative results of the multi-objective methods.

Scenario #	Methods	Objective satisfaction degrees				TWSD
		Obj. 1	Obj. 2	Obj. 3	Obj. 4	
1	Goal programming	80.73%	100%	14.41%	80%	69.39%
	Max–min	80.45%	95.02%	94.37%	93.62%	90.97%
	This study	*76.72%*	*96%*	*100%*	*100%*	*93.03%*
2	Goal programming	78.92%	100%	13.49%	80%	68.71%
	Max–min	77.51%	90.14%	80.91%	77.30%	82.13%
	This study	*73.16%*	*96.58%*	*100%*	*100%*	*92.32%*
3	Goal programming	78%	100%	12.89%	80%	68.32%
	Max–min	81.63%	83.87%	81.63%	81.63	82.30%
	This study	*73.85%*	*94.91%*	*100%*	*100%*	*91.99%*

Table 18
Results of the sensitivity analysis (Scenario-1).

Sub-scenario #	Objective weights				Objective satisfaction degrees				TWSD
	Obj. 1	Obj. 2	Obj. 3	Obj. 4	Obj. 1	Obj. 2	Obj. 3	Obj. 4	
1	*0.100*	0.359	0.306	0.235	62.54%	97.95%	96.24%	95.74%	93.37%
2	*0.200*	0.319	0.272	0.209	73.47%	97.37%	100%	100%	93.85%
3	*0.300*	0.279	0.238	0.182	77.00%	95.49%	100%	100%	91.74%
4	*0.400*	0.239	0.204	0.156	77.99%	95.47%	100%	100%	90.01%
5	*0.500*	0.199	0.170	0.130	77.75%	95.59%	100%	100%	87.90%
6	0.319	*0.100*	0.329	0.252	73.96%	95.41%	100%	100%	91.23%
7	0.283	*0.200*	0.293	0.224	77.70%	95.66%	100%	100%	92.82%
8	0.248	*0.300*	0.256	0.196	76.72%	96.00%	100%	100%	93.03%
9	0.213	*0.400*	0.219	0.168	73.57%	98.41%	100%	100%	93.74%
10	0.177	*0.500*	0.183	0.140	73.57%	98.41%	100%	100%	94.53%
11	0.300	0.363	*0.100*	0.237	74.89%	97.36%	96.24%	95.74%	90.12%
12	0.267	0.323	*0.200*	0.211	76.28%	96.12%	100%	100%	92.51%
13	0.233	0.282	*0.300*	0.184	76.62%	96.14%	100%	100%	93.37%
14	0.200	0.242	*0.400*	0.158	77.33%	95.94%	100%	100%	94.48%
15	0.167	0.202	*0.500*	0.132	76.12%	95.53%	100%	100%	95.21%
16	0.278	0.336	0.287	*0.100*	77.55%	95.69%	100%	100%	92.41%
17	0.247	0.299	0.255	*0.200*	77.59%	95.79%	100%	100%	93.31%
18	0.216	0.261	0.223	*0.300*	76.95%	96.00%	100%	100%	93.98%
19	0.185	0.224	0.191	*0.400*	74.12%	97.62%	100%	100%	94.68%
20	0.154	0.187	0.159	*0.500*	73.27%	96.17%	96.24%	95.74%	92.44%

value of total weighted satisfaction degree when compared with the other two methods.

6.2. Sensitivity analysis

In addition to the comparative analysis, sensitivity analysis is also performed by considering the objective importance weights. Accordingly, objectives are considered one by one and the importance weight of each selected objective is changed while the other objectives' importance weights remained stable. Within the analyses, five scenarios are generated for the importance of each objective and the importance weights of 0.1, 0.2, 0.3, 0.4 and 0.5 are considered, respectively. Therefore, a total of 60 sub-scenarios are analyzed regarding the four objectives. The satisfaction degree of each objective function and the total weighted satisfaction degree are obtained for each sub-scenario and indicated in Tables 18–20.

For the first scenario (Table 18), where the total quantity to be collected is around 1180 tons, the minimum level of TWSD is determined as 87.90% for the 5th sub-scenario where the weights are determined as 0.500; 0.199; 0.170 and 0.130 for the objectives 1,2,3 and 4, respectively. The maximum level is determined as 95.21% in the 15th sub-scenario. Therefore, a 7.31% interval is calculated between minimum and maximum scores. The fact that the variation interval is not high indicates the strength of the model against changes.

For the second scenario (Table 19), where the total quantity to be collected is around 1448 tons, the minimum score is achieved in the 5th sub-scenario whereas the maximum score is in the 1st sub-scenario. The interval between minimum and maximum scores is 10.19% which still shows the proposed model's strength against the changes in weights.

For the third scenario (Table 20), where the total quantity to be collected is around 1717 tons, the minimum score is achieved again in the 5th sub-scenario whereas the maximum score is in the 1st sub-scenario. However, the interval between minimum and maximum scores is calculated as 10.78% which is slightly higher than the one in the second scenario.

In all of the three main scenarios, analysis of sub-scenarios based on TWSD showed that the proposed model is robust under the changes in weights. On the other hand, when these intervals are examined separately for each objective function basis, it is seen that the most sensitive change is realized within the first objective (cost).

In addition, the detailed examinations revealed that there seems to be a correlation between the third and fourth objectives while there is a conflicting structure between the first and second objectives, in all three main scenarios. In other words, as the weight of the cost objective function (Objective function 1) is increased, the satisfaction degree value of objective function 2, which aims at minimizing carbon emissions, decreases. The opposite has also been observed. It is seen that this situation between

Table 19
Results of the sensitivity analysis (Scenario-2).

Sub-scenario #	Objective weights				Objective satisfaction degrees				TWSD
	Obj. 1	Obj. 2	Obj. 3	Obj. 4	Obj. 1	Obj. 2	Obj. 3	Obj. 4	
1	*0.100*	0.359	0.306	0.235	67.35%	97.31%	100%	100%	95.77%
2	*0.200*	0.319	0.272	0.209	69.57%	97.06%	99.36%	99.28%	92.65%
3	*0.300*	0.279	0.238	0.182	71.77%	95.41%	100%	100%	90.15%
4	*0.400*	0.239	0.204	0.156	75.77%	95.17%	99.36%	99.28%	88.81%
5	*0.500*	0.199	0.170	0.130	73.68%	95.17%	99.36%	99.28%	85.58%
6	0.319	*0.100*	0.329	0.252	65.58%	97.2%	100%	100%	88.74%
7	0.283	*0.200*	0.293	0.224	72.91%	95.07%	100%	100%	91.35%
8	0.248	*0.300*	0.256	0.196	73.16%	96.58%	100%	100%	92.32%
9	0.213	*0.400*	0.219	0.168	71.81%	97.36%	100%	100%	92.94%
10	0.177	*0.500*	0.183	0.140	68.75%	97.78%	100%	100%	93.36%
11	0.300	0.363	*0.100*	0.237	74.70%	96.11%	100%	100%	91%
12	0.267	0.323	*0.200*	0.211	70.19%	95.41%	100%	100%	90.66%
13	0.233	0.282	*0.300*	0.184	75.52%	95.56%	100%	100%	92.95%
14	0.200	0.242	*0.400*	0.158	68.34%	95.41%	100%	100%	92.56%
15	0.167	0.202	*0.500*	0.132	72.89%	95.82%	100%	100%	94.73%
16	0.278	0.336	0.287	*0.100*	71.68%	96.22%	99.36%	99.28%	90.7%
17	0.247	0.299	0.255	*0.200*	72.72%	95.41%	100%	100%	91.99%
18	0.216	0.261	0.223	*0.300*	71.8%	96.93%	100%	100%	93.11%
19	0.185	0.224	0.191	*0.400*	72.67%	96.16%	100%	100%	94.08%
20	0.154	0.187	0.159	*0.500*	74.50%	95.17%	99.36%	99.28%	94.71%

Table 20
Results of the sensitivity analysis (Scenario-3).

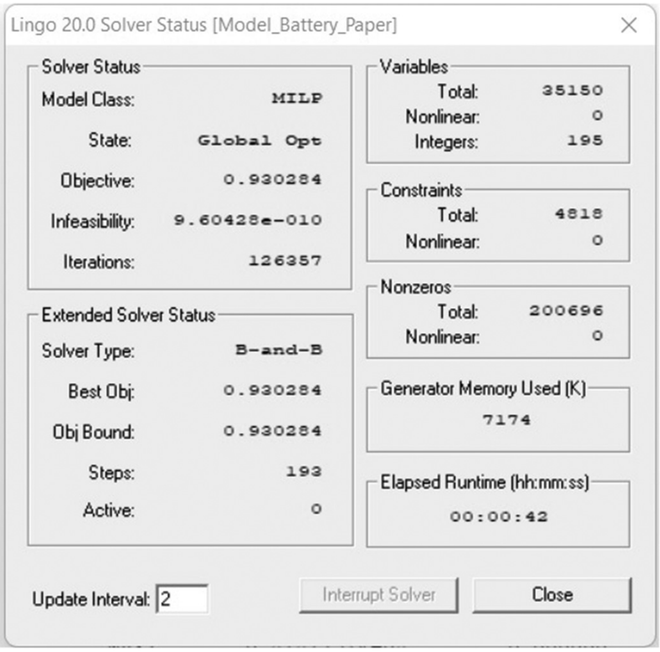
Sub-scenario #	Objective weights				Objective satisfaction degrees				TWSD
	Obj. 1	Obj. 2	Obj. 3	Obj. 4	Obj. 1	Obj. 2	Obj. 3	Obj. 4	
1	*0.100*	0.359	0.306	0.235	65.49%	96.62%	100%	100%	95.34%
2	*0.200*	0.319	0.272	0.209	71.21%	97.08%	100%	100%	93.31%
3	*0.300*	0.279	0.238	0.182	73.65%	94.91%	100%	100%	90.57%
4	*0.400*	0.239	0.204	0.156	67.51%	95.67%	100%	100%	85.87%
5	*0.500*	0.199	0.170	0.130	71.51%	94.52%	100%	100%	84.56%
6	0.319	*0.100*	0.329	0.252	69.16%	94.49%	100%	100%	89.61%
7	0.283	*0.200*	0.293	0.224	74.58%	94.88%	100%	100%	91.78%
8	0.248	*0.300*	0.256	0.196	73.85%	94.91%	100%	100%	91.99%
9	0.213	*0.400*	0.219	0.168	71.74%	97.08%	100%	100%	92.81%
10	0.177	*0.500*	0.183	0.140	65.13%	97.08%	100%	100%	92.37%
11	0.300	0.363	*0.100*	0.237	68.96%	94.91%	100%	100%	88.84%
12	0.267	0.323	*0.200*	0.211	71.93%	95.86%	100%	100%	91.27%
13	0.233	0.282	*0.300*	0.184	72.13%	96.25%	100%	100%	92.35%
14	0.200	0.242	*0.400*	0.158	72.39%	96.57%	100%	100%	93.65%
15	0.167	0.202	*0.500*	0.132	67.97%	96.38%	100%	100%	94.02%
16	0.278	0.336	0.287	*0.100*	71.93%	96.25%	100%	100%	91.04%
17	0.247	0.299	0.255	*0.200*	73.93%	95%	100%	100%	92.17%
18	0.216	0.261	0.223	*0.300*	68.59%	95.42%	100%	100%	92.02%
19	0.185	0.224	0.191	*0.400*	67.01%	94.91%	100%	100%	92.76%
20	0.154	0.187	0.159	*0.500*	69.56%	95.86%	100%	100%	94.54%

the two objective values is expected when the parameters of the model are re-examined. The main reason for this opposition is the location of the eastern provinces having low carbon emission levels. When eastern provinces are selected for the minimization of carbon emission levels, the transportation cost increases due to the long distances between the east and the highly populated western provinces having the majority of the battery waste.

7. Conclusion

Reverse logistics plays an important role in providing the sustainability of supply chains. Various topics are considered within the reverse logistics subject. However, network design comes to the front depending on its main effect on various fields including economic issues, environmental concerns, and socio-economy. On the other hand, the variety of used products is also high in reverse logistics networks. In this study, waste batteries are handled and network design is performed with a two-stage methodology under multiple objectives. In the first stage of the methodology, the importance weights of the objectives are determined via SF-AHP. Afterward, in the second stage, a multi-objective MILP model is utilized for maximizing the total weighted satisfaction degree of multiple objectives including the minimization of cost and carbon emission and the maximization of employment and development rates.

The proposed methodology is applied to the network design of waste batteries in Turkey step by step to make it more understandable. Within the first stage, SF-AHP is utilized by getting expert views in the field and the importance weights of the objectives are found as cost minimization (0.248), carbon emission minimization (0.3), employment rate maximization (0.256) and development rate maximization (0.196). Afterward, the MO-MILP model is run for the maximization of the TWSD under three scenarios including the forecasted quantities for the years 2023,



```
Lingo 20.0 Solver Status [Model_Battery_Paper]

Solver Status
Model Class:          MILP
State:          Global Opt
Objective:        0.930284
Infeasibility: 9.60428e-010
Iterations:         126357

Extended Solver Status
Solver Type:        B-and-B
Best Obj:          0.930284
Obj Bound:         0.930284
Steps:                  193
Active:                   0

Variables
Total:        35150
Nonlinear:        0
Integers:       195

Constraints
Total:         4818
Nonlinear:        0

Nonzeros
Total:       200696
Nonlinear:        0

Generator Memory Used (K)
7174

Elapsed Runtime (hh:mm:ss)
00:00:42

Update Interval: 2
```

Fig. A.1. The snapshot of the LINGO optimization program indicating the result in the first scenario.

2028 and 2033. The locations and types of the storage areas and the recycling facilities are obtained.

Considering the limitations of this study, it can be stated that there is limited historical data available in Turkey since the recycling of waste batteries has been newly started. Therefore, there are shortcomings and uncertainties about the values of some parameters. With the realization of applications in a reasonable time period, it will be possible to design networks with more reliable data. However, in the near future, stochastic and fuzzy models can be developed so that uncertainties can be represented in the mathematical model. Moreover, different MADM techniques can be used for determining the importance weights of the objectives and the proposed methodology can be extended for other waste types.

CRediT authorship contribution statement

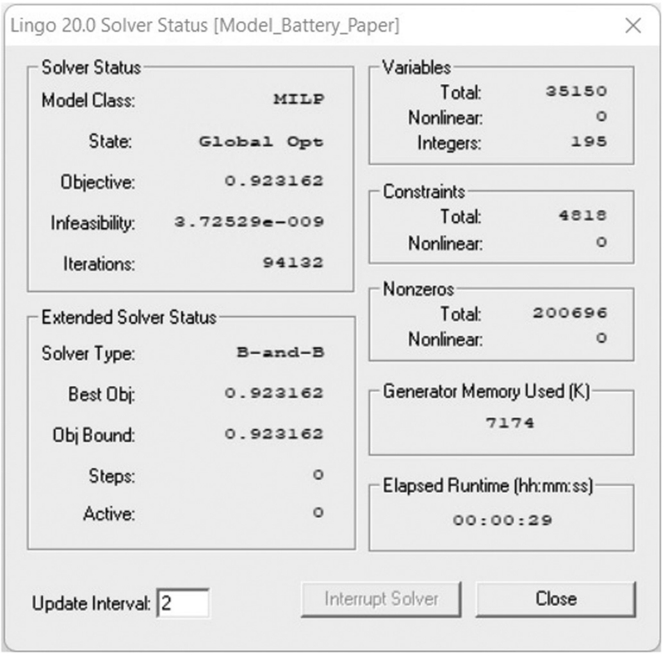
Huseyin Selcuk Kilic: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Zeynep Tugce Kalender:** Methodology, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Buse Solmaz:** Investigation, Resources, Data curation. **Demet Iseri:** Investigation, Resources, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

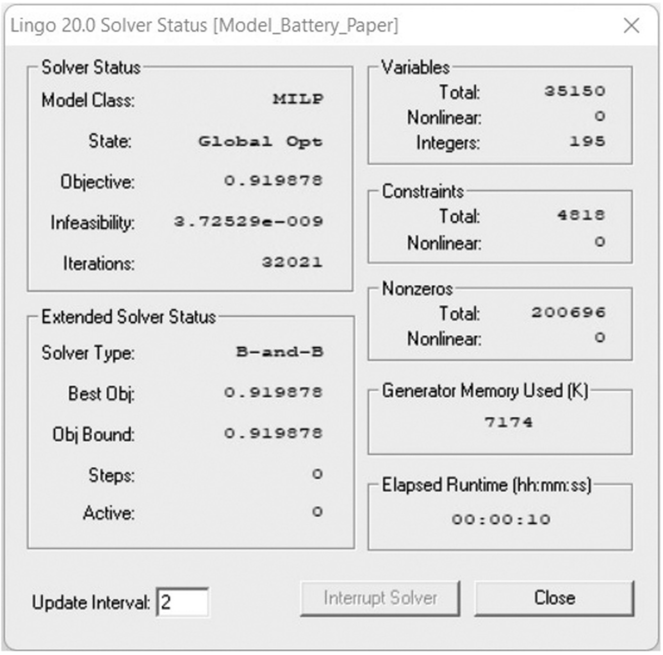
Appendix. Snapshots of the LINGO program

See Figs. A.1–A.3.



```
Lingo 20.0 Solver Status [Model_Battery_Paper]

Solver Status
Model Class:          MILP
State:          Global Opt
Objective:        0.923162
Infeasibility: 3.72529e-009
Iterations:          94132

Extended Solver Status
Solver Type:        B-and-B
Best Obj:          0.923162
Obj Bound:         0.923162
Steps:                    0
Active:                   0

Variables
Total:        35150
Nonlinear:        0
Integers:       195

Constraints
Total:         4818
Nonlinear:        0

Nonzeros
Total:       200696
Nonlinear:        0

Generator Memory Used (K)
7174

Elapsed Runtime (hh:mm:ss)
00:00:29

Update Interval: 2
```

Fig. A.2. The snapshot of the LINGO optimization program indicating the result in the second scenario.



```
Lingo 20.0 Solver Status [Model_Battery_Paper]

Solver Status
Model Class:          MILP
State:          Global Opt
Objective:        0.919878
Infeasibility: 3.72529e-009
Iterations:          32021

Extended Solver Status
Solver Type:        B-and-B
Best Obj:          0.919878
Obj Bound:         0.919878
Steps:                    0
Active:                   0

Variables
Total:        35150
Nonlinear:        0
Integers:       195

Constraints
Total:         4818
Nonlinear:        0

Nonzeros
Total:       200696
Nonlinear:        0

Generator Memory Used (K)
7174

Elapsed Runtime (hh:mm:ss)
00:00:10

Update Interval: 2
```

Fig. A.3. The snapshot of the LINGO optimization program indicating the result in the third scenario.

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